Airborne Lidar Simulator for the Lidar Surface Topography (LIST) Mission

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Earth Science Technology Forum 2010
ESTF2010 – Paper A7P2
Crystal City, VA
24 June 2010

Efficient Swath Mapping Laser Altimetry Demonstration

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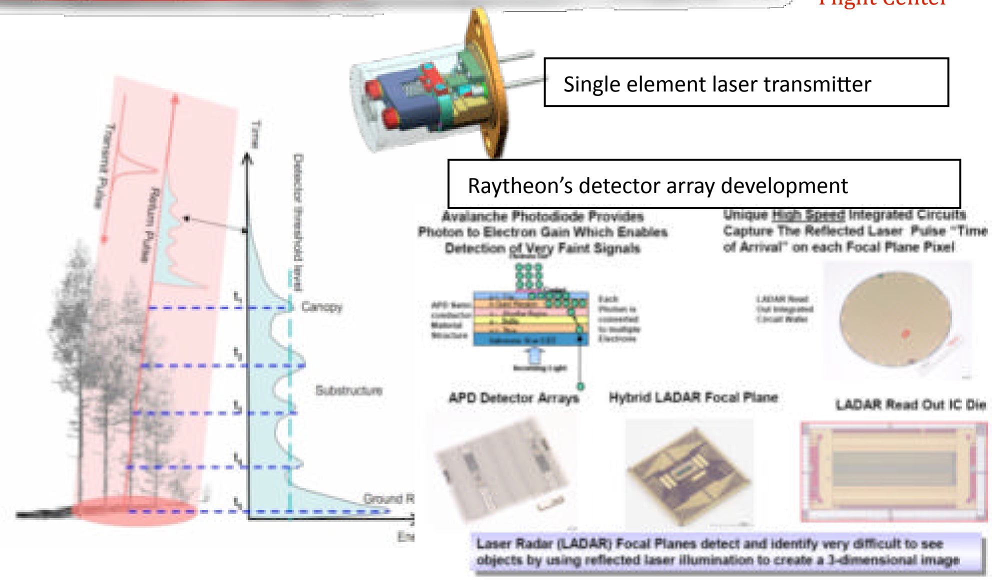
Objective

- Develop technologies for a swath mapping, space altimeter to enable 5-m spatial resolution topography and vegetation vertical structure, with decimeter vertical precision, in support of the Land Surface Topography (LIST) mission
  - Develop and demonstrate a >15% wall plug efficient laser system coupled with a highly sensitive detector array to realizing the global elevation mapping goals of the LIST mission
- Demonstrate accurate measurements on the ground and from an aircraft as a pathfinder and as a simulator for LIST



Approach

- Develop, demonstrate and evaluate single laser transmitter and single element receiver meeting system requirement
- Assemble and evaluate a 1-channel breadboard
- Develop, demonstrate and evaluate a 4x4 laser array and 4x4 receiver array for a 16-channel prototype
- Assemble, flight test, and evaluate a 16-channel prototype

Co-Is/Partners: James Abshire, Xiaoli Sun, David Harding, and Michael Krainak, GSFC;
Alexander Betin, Raytheon Space and Airborne Systems; Jinxue Wang, Raytheon Vision Systems

Key Milestones

• Conduct single laser/receiver channel PDR	07/09
• Conduct single laser/receiver channel CDR	08/09
• Conduct end-to-end system test of the single laser/receiver channel	01/10
• Conduct multi-element laser/receiver array PDR	01/10
• Conduct multi-element laser/receiver array CDR	04/10
• Conduct end-to-end system test of the multi-element laser/receiver array	10/10
• Perform engineering test flight(s) aboard LearJet 25	06/11
• Perform science flight(s) aboard LearJet 25	08/11

$TRL_{in} = 3$ $TRL_{exit} = 5$

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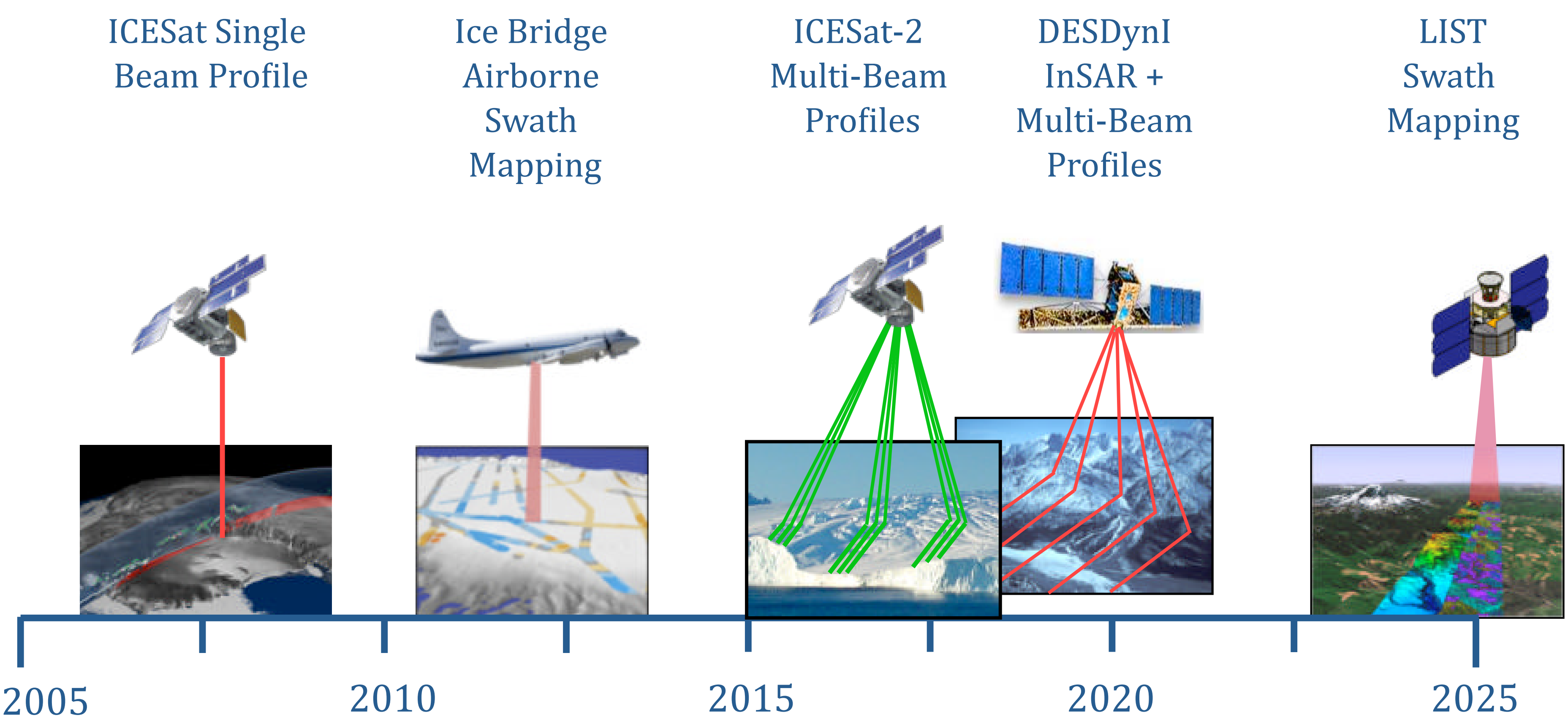
Outline

- Introduction
- LIST Science Objectives & Requirements
- Lidar Measurement Approach & Performance Analysis
- Airborne Instrument Development
- Summary

LIDAR SURFACE TOPOGRAPHY (LIST)
SCIENCE OBJECTIVES & REQUIREMENTS

LIST Mission Context

Evolution of NASA Earth Science Laser Altimeter Missions



NRC Earth Science Decadal Survey Missions

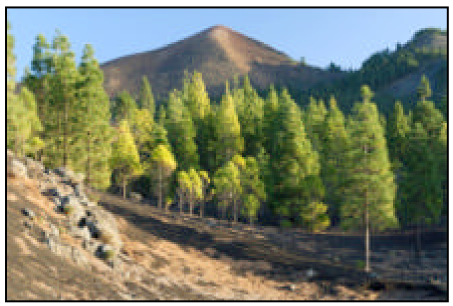
LIST Science Objectives

LIST will provide high-resolution elevation images of the Earth's solid surface & its overlying covers of vegetation, water, snow, ice and manmade structures.

This foundation data is fundamental to understanding, modeling and predicting interactions between the tectosphere, hydrosphere, biosphere, cryosphere and atmosphere.

Solid Earth

- landscape evolution
- climate/tectonics/erosion interactions
- earthquake, volcano, landslide and coastal hazards



Vegetation Structure

- carbon storage
- disturbance & response
- habitat and biodiversity
- wild-fire fuel loads
- slope stabilization

Cryosphere

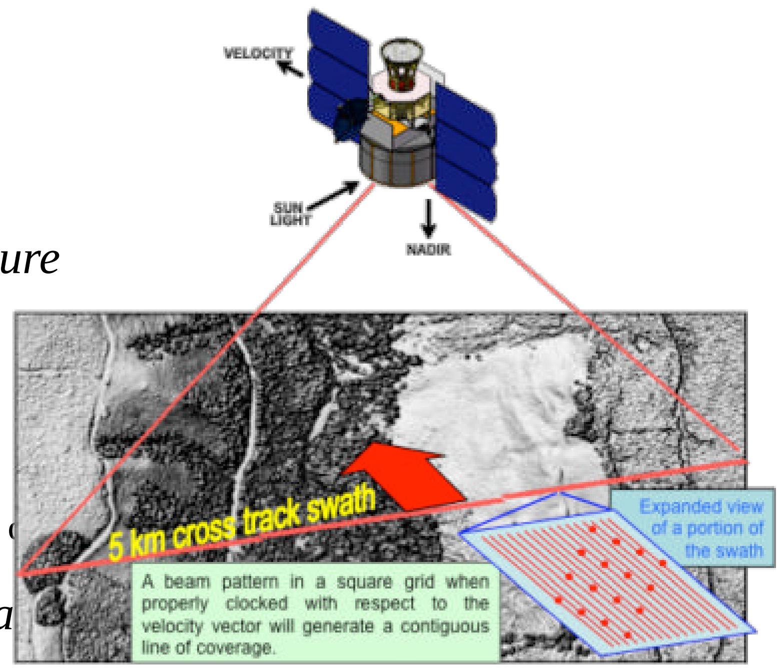
- ice sheet, ice cap and glacier elevation change
- ice flow and dynamics
- sea ice cover & thickness

Water Cycle

- water storage
- snow depth
- river discharge

LIST Measurement Requirements

- *Acquire elevation images of land topography, including where covered by vegetation, and ice sheets, glaciers and snow cover*
  - 5 m spatial resolution (i.e., pixel size)
  - ≤ 10 cm relative vertical accuracy per 5 m pixel for flat surfaces
  - ≤ 20 cm absolute vertical accuracy per 5 m pixel for flat surfaces
- *Acquire images of vegetation height and vertical structure*
  - 1 m vertical resolution per 25 m x 25 m area
- *Complete one-time global mapping in ≤ 3 years*
  - Implies a 5 km or wider swath to build up coverage during clear sky
- *Repeat mapping for change monitoring in selected area*
  - Monthly for water storage and natural hazard topographic change
  - Seasonally for ice sheet, sea ice and vegetation structure change



LIST - Challenges for a Space Lidar

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- 1000 parallel profiling lines (or channels):
  - Each line measures 5 m ground spots at 1.4 kHz measurement rate
  - Detecting ground echoes through tree canopies (2% opening) under clear sky conditions (~60-70% one way transmission)
  - Alignment of 1000 transmit beams to receiver detector elements
  - 1000 channel data acquisition, processing, and storage
- Resource Goals: < 10 KW peak electrical power and <700 kg mass
  - Implies < 10W electrical power/channel
- **Need approach with high "measurement efficiency"**
  - High laser 'wall-plug efficiency'
  - High receiver sensitivity – single photon detection
  - Wide receiver dynamic range: detect ground echoes under trees
- Practical receiver signal processing and hardware

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LIST Challenges and IIP's Risks Reduction Approach

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	LIST Challenges	Demonstrate with IIP	Comments
Number of profiling lines	1000 parallel profiling lines	16 parallel profiling lines	Demonstrate beam division technique
Measurement Rate	Each line measures 5-m ground spots at 1.4 kHz measurement rate	Each line measures 5-m ground spots at 1.4 kHz measurement rate	The airborne demo will oversample by ~35X.
Detection Condition	Detecting ground echoes through tree canopies (5% opening) under clear sky conditions (~70% one way transmission)	Detecting ground echoes through tree canopies (5% opening) under clear sky conditions (~70% one way transmission)	Demonstrate measurement sensitivity and waveform processing to sample canopy substructure
Alignment Sensitivity	Alignment of 1000 transmitters with receiver optics	Alignment of 16 transmitted beam with receiver optics	Retiring some of the risks of multiple boresight alignment
Data Processing	1000 channel data acquisition, processing, and storage	16 channel data acquisition, processing, and storage	Demonstrate the feasibility of needed data processing
Resources	<7 kW peak electrical power. Assuming 15% laser efficiency. Implies <7W electrical power per profiling line	<0.1 kW peak electrical power. Assuming 15% laser efficiency. Implies <7W electrical power per profiling line	Demonstrate laser efficiency of microchip laser and planar waveguide amplifier architecture
Laser	1000 laser beams with 100 µJ per beam @ 10 kHz; Possible 10 Lasers each with 100 beams	16 laser beams with 100 µJ per beam @ 10 kHz; Also demonstrate 20 pm spectral width.	Demonstrate narrow linewidth laser with power scalable for space
Detector	1000 pixel photon counting array with single photon sensitivity, each pixel with > 1 GHz bandwidth and ROIC for waveform readout	16 pixel photon counting array with single photon sensitivity, each pixel with > 1 GHz bandwidth and ROIC for waveform readout	Demonstrate state-of-the-art photon counting detector technology

Airborne Swath Mapper Topography Requirements

- Acquire elevation images of land topography (Digital Elevation Model)
  - 5 x 5 m spatial resolution (i.e., pixel size)
  - ≥ 80 m cross-track swath width (image geomorphic features)
  - Relative accuracy (1 sigma) (same as spaceflight requirement)
    - 0.5 m horizontal between pixels
    - 0.1 m vertical between pixels for 1° slope
    - 0.5 m vertical between pixels for 10° slope
  - Absolute accuracy (1 sigma) (3x less than spaceflight requirement, sufficient for airborne demonstration purposes; a function of GPS/INS instrumentation)
    - 6 m horizontal
    - 0.6 m vertical for 1° slope
    - 2.4 m vertical for 10° slope
  - Specifications defined for measurement conditions of:
    - Canopy cover such that 2% of return energy is from ground
    - 60% one-way atmospheric transmission

Airborne Swath Mapper Vegetation Requirements

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- Acquire images of vegetation height and vertical structure
  - ≤ 25 x 25 m spatial resolution (i.e., pixel size); smaller is preferred
    - aggregate ≤ 5 x 5 ground topography pixels
  - ≥ 80 m cross-track swath width (≥ 3 pixels wide)
  - 1 m canopy height accuracy, relative to the ground, for 5th, 25th, 50th and 75th % of cumulative received signal from canopy and ground (1 sigma)
    - 50th % = Height of Median Energy (HOME) = waveform centroid
  - 1.5 m relative height accuracy for interior canopy layers (1 sigma)
  - Specifications defined for measurement conditions of:
    - Canopy cover such that 2% of return energy is from ground
    - Outer canopy rise time: 8% of received energy over 8 m
    - 60% one-way atmospheric transmission
    - 1° ground slope

Airborne Swath Mapper Geometry

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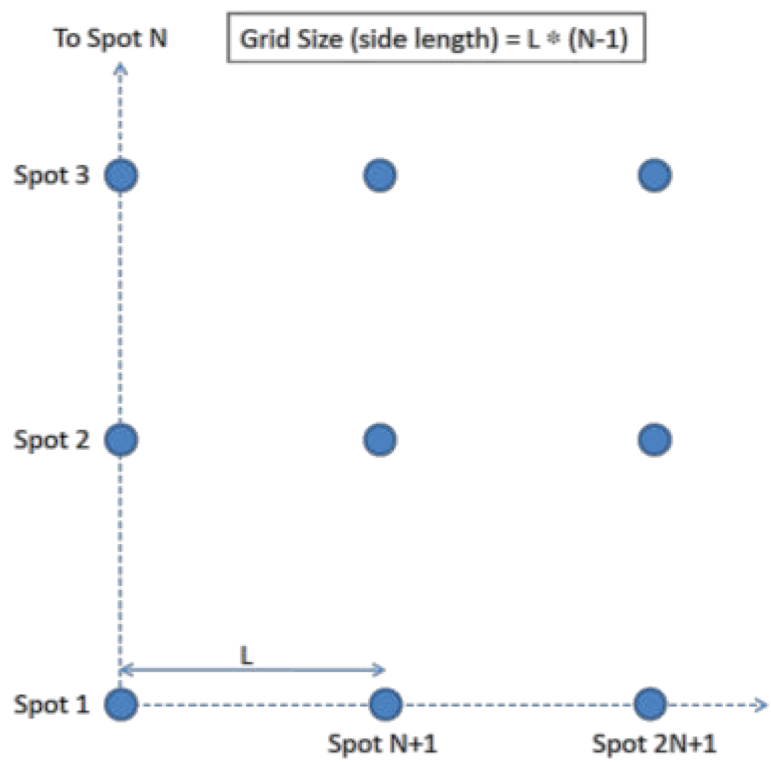
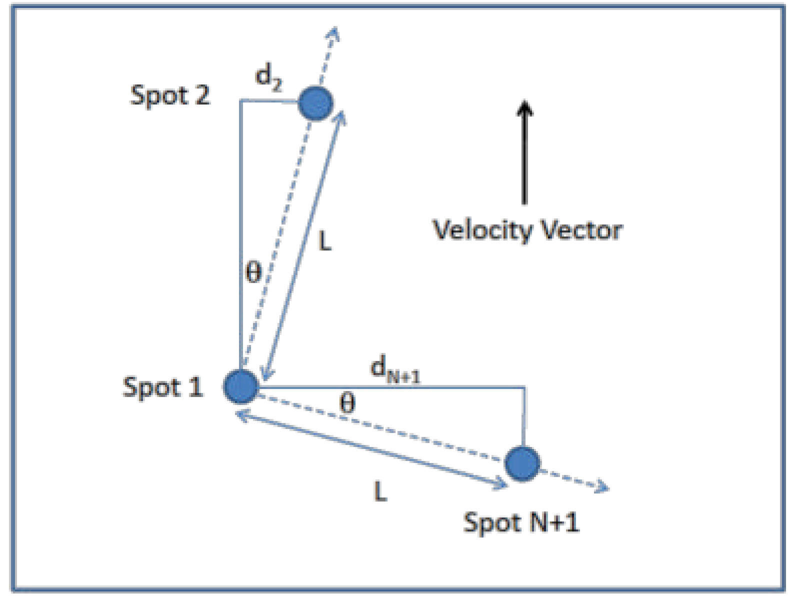
N x N Square Grid of Laser Spots



Clock Array to get Equal Track Spacing



For equal track spacing want: $Nd_2 = d_{N+1}$
where $d_2 = L*SIN(\theta)$ and $d_{N+1} = L*COS(\theta)$

Solving using the above three equations we find: $\boxed{TAN(\theta) = 1/N}$
where θ is the clocking angle required to obtain equal track spacing for a square grid

Square Grid Size and Clocking to Obtain Equal Track Spacing LRI 21-Jun-10

Design	# Spots	Grid	Track spacing (m)	Swath (m)	Grid spacing L (m)	Grid size (m)	Grid clocking θ (deg)
IIP - A	16	4 x 4	5	80	20.6	61.8 x 61.8	14.036

Airborne Swath Mapper Measurement Geometry

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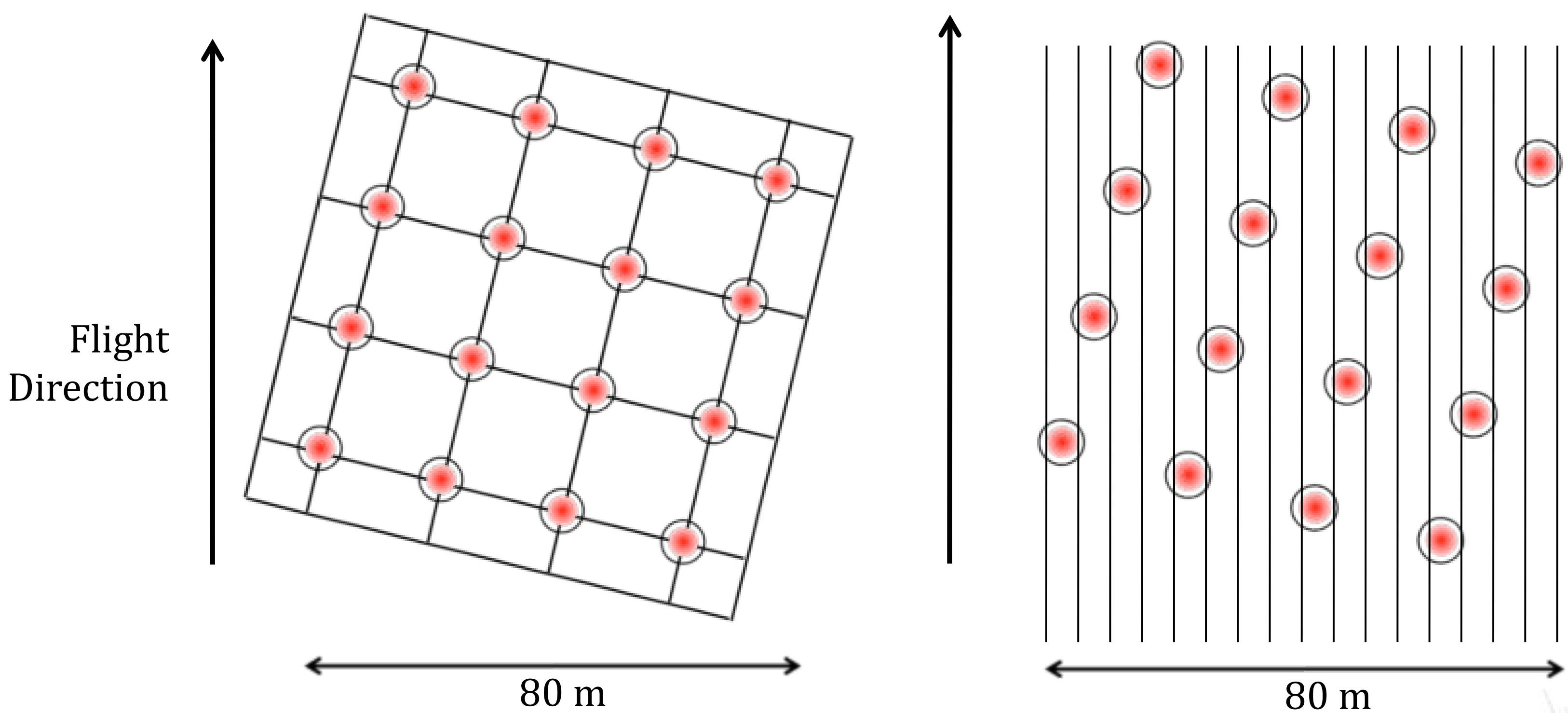
- Altitude = 10 km:
- Detector FOV = 7 m (0.7 mrad); Laser Spot = 5 m (0.5 mrad); Spot Spacing = 20 m (2 mrad)
- Yaw rotation of 14.5° yields uniformly spaced spots with 5 m horizontal spacing
- Detector FOV's separated to prevent cross-talk
- 16 contiguous, cross-track, 5 m wide profiles in flight direction



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Spaceborne and Airborne Measurement Comparison

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Parameters	Spaceborne Instrument	Airborne Instrument	Comments
Spatial Resolution	5 meter	5 meter	Use the same footprint, rather than scaled by angular divergence
Altitude	400 km	10 km	Scale: 40X
Swath Width	5 km (1000 beams)	80 m (16 beams)	Scale: 62.5X
Detection Scheme	Waveform capturing and analysis	Waveform capturing and analysis	Backup Option – Geiger Mode Photon Counting on Airborne Instrument
Laser Energy	100 μJ per beam for 1000 beam @ 10 kHz – 1 kW optical power or 6.7kW prime power assuming 15% efficiency	100 μJ per beam for 16 beam @ 10 kHz – 16 W optical power or 110 W prime power	Demonstration of full energy per beam meeting LIST's spaceborne instrument requirement.
Detector	1000 pixels with > 1 GHz bandwidth on each pixel	16 pixels with > 1 GHz bandwidth on each pixel	Demonstrate the necessary bandwidth in multiple pixel detector array with photon counting sensitivity
Platform Speed	7000 m/sec	200 m/sec	Scale: 35X
Number of samples per footprint	7	250	During the Airborne campaign, we can sample every 35th one to simulate space environment
Footprint Separation	0.7 meter	0.02 meter	Airborne will oversample by 35X
Beam dividing network	One scenario is to have 10 lasers, each with 1x100 beam divider DOE	Single laser beam divides into 16 beam using a DOE	Demonstrate efficient beam division technique
Spectral Linewidth	< 20 pm	< 20 pm	Demonstrate the technical approach to stabilize laser wavelength and spectral width when use with narrow Rx filter

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LIDAR MEASUREMENT APPROACH & PERFORMANCE ANALYSIS

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LIST Measurement Approach

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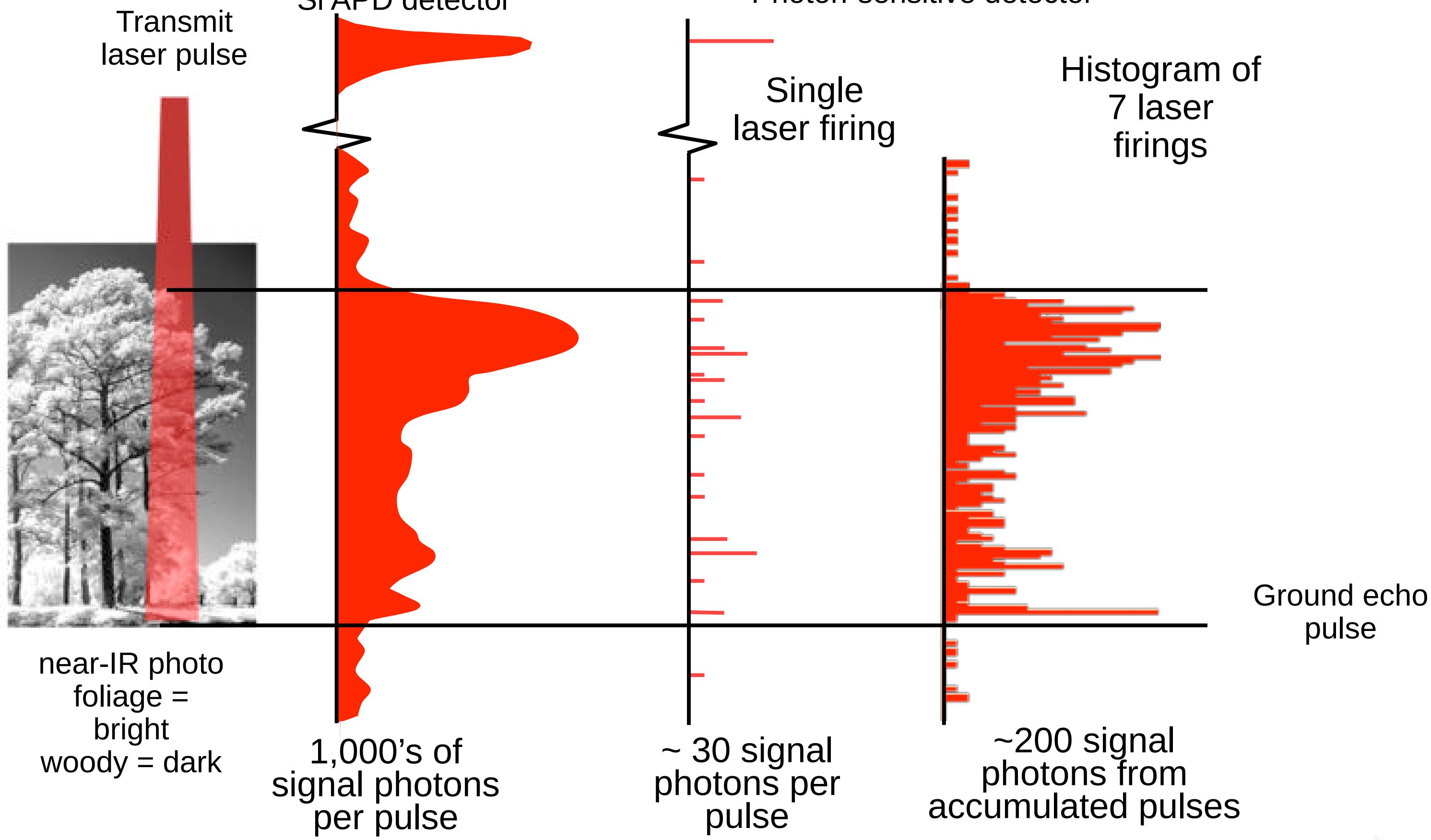
GLAS & DesdynI:
Single Pulse Analog
3 nsec pulse width
~3 mJ per pulse
1400 Hz
Si APD detector

LIST:
Micropulse Photon Counting
1 nsec pulse width
50 µJ per pulse
10 kHz
Photon-sensitive detector



LIST with 1030 nm PMT Detection - Space - NIR PMT Single Photon Sensitivity

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Approach:

Photon sensitive detection
PMT -> analog digitizer
Multiple laser pulse histogramming
NIR-PMT detector: 10% QE

Laser Illumination:

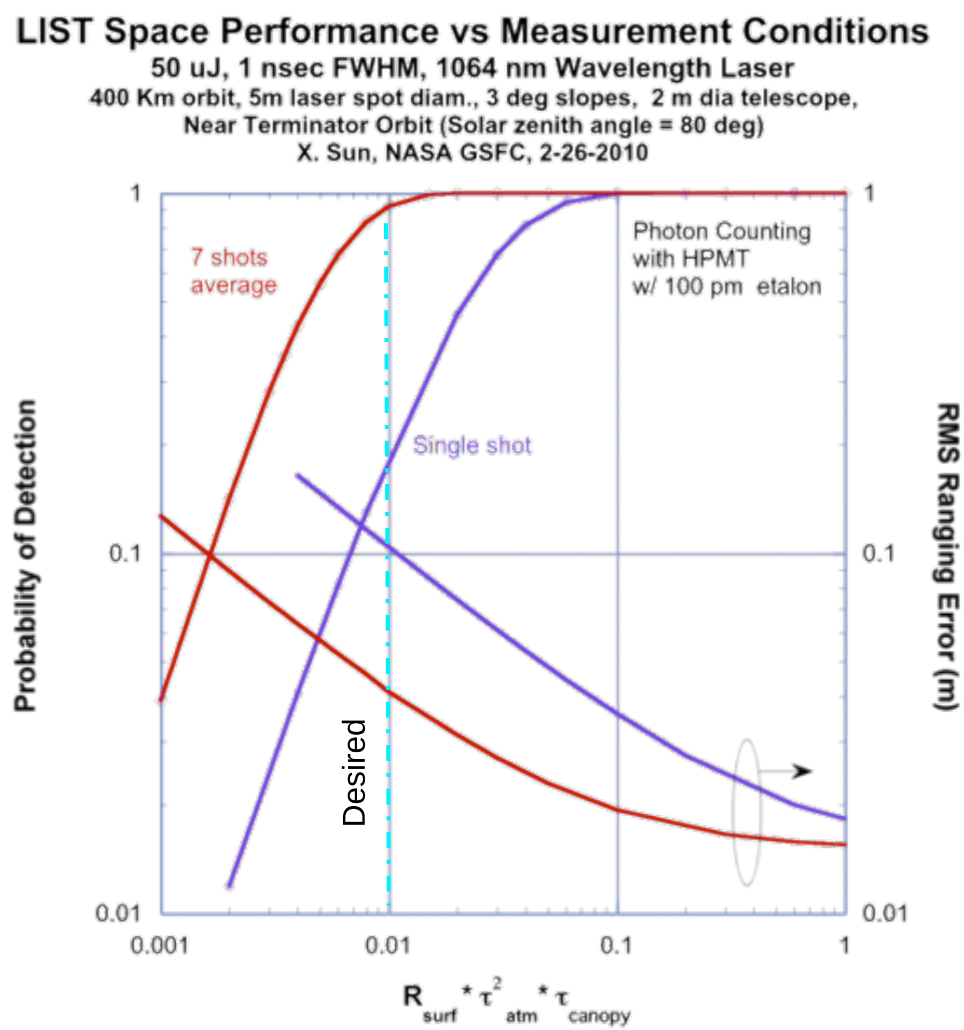
Laser fire rate along track: 10 KHz
Laser firings/pixel: 7
Laser energy/pulse: 50 uJ
Ave Power/track: 0.5 W
Ave Laser E. Power/track: 5 W
Meets LIST efficiency goals

Detection Probability:

>90% after averaging received signal over 7 laser shots

Range jitter:

Vertical offset - laser pulse range spread
Floor set - digitizer rate (1.5 GHz)



- *NIR PMT detection improves receiver sensitivity by x7*

Model From: Harding IIP-04

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1030 nm PMT Detection - Airborne Simulator -NIR HPMT in Single Photon Counting Mode

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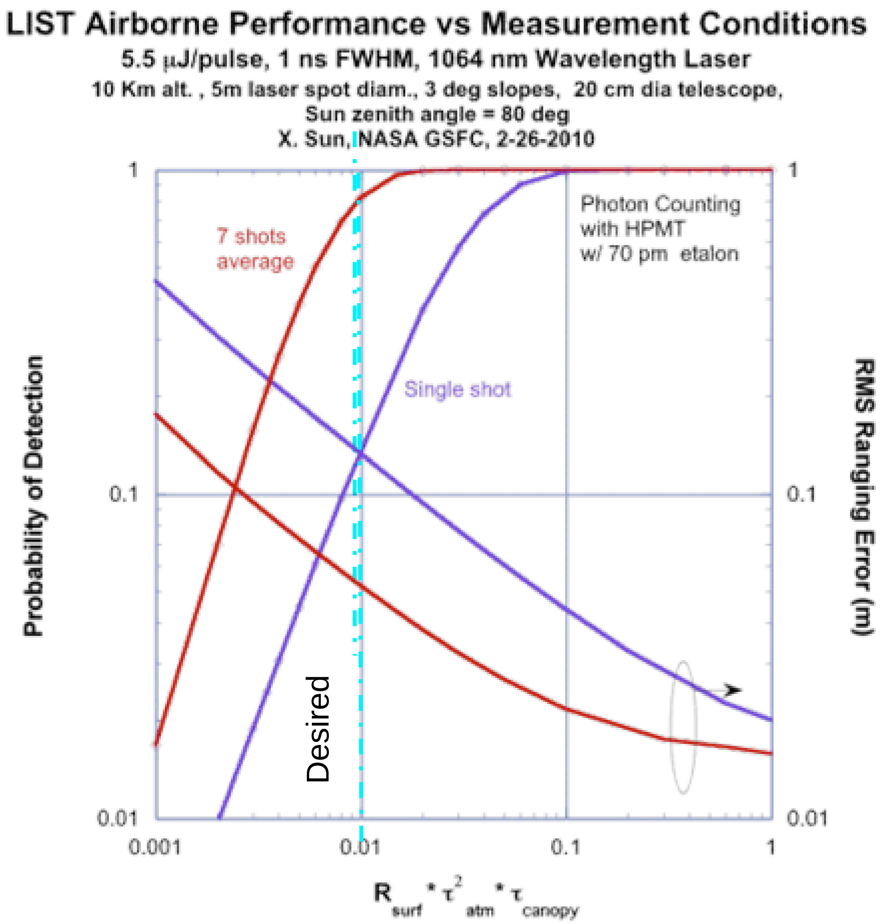
Approach:

Same approach as for space, but:
Lower altitude: 10 vs 400 km
Smaller telescope: 0.2 vs 2 m
Lower laser energy: 5 vs 50 µJ
Lower pulse rate: 2 vs 10 KHz

Airborne lidar at 10 km & ~ 5 uJ per spot is good simulator for LIST space lidar:

- *Similar performance*
- *Relative scaling factor can be adjusted via aircraft altitude*
- *At 200 m/sec speed, laser fires 50 times per pixel*
  - *Allows x7 oversampling*
- *Measurements can be decimated post flight, as needed for analysis*



Model From: Harding IIP-04

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AIRBORNE INSTRUMENT DEVELOPMENT

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Airborne Instrument Objectives

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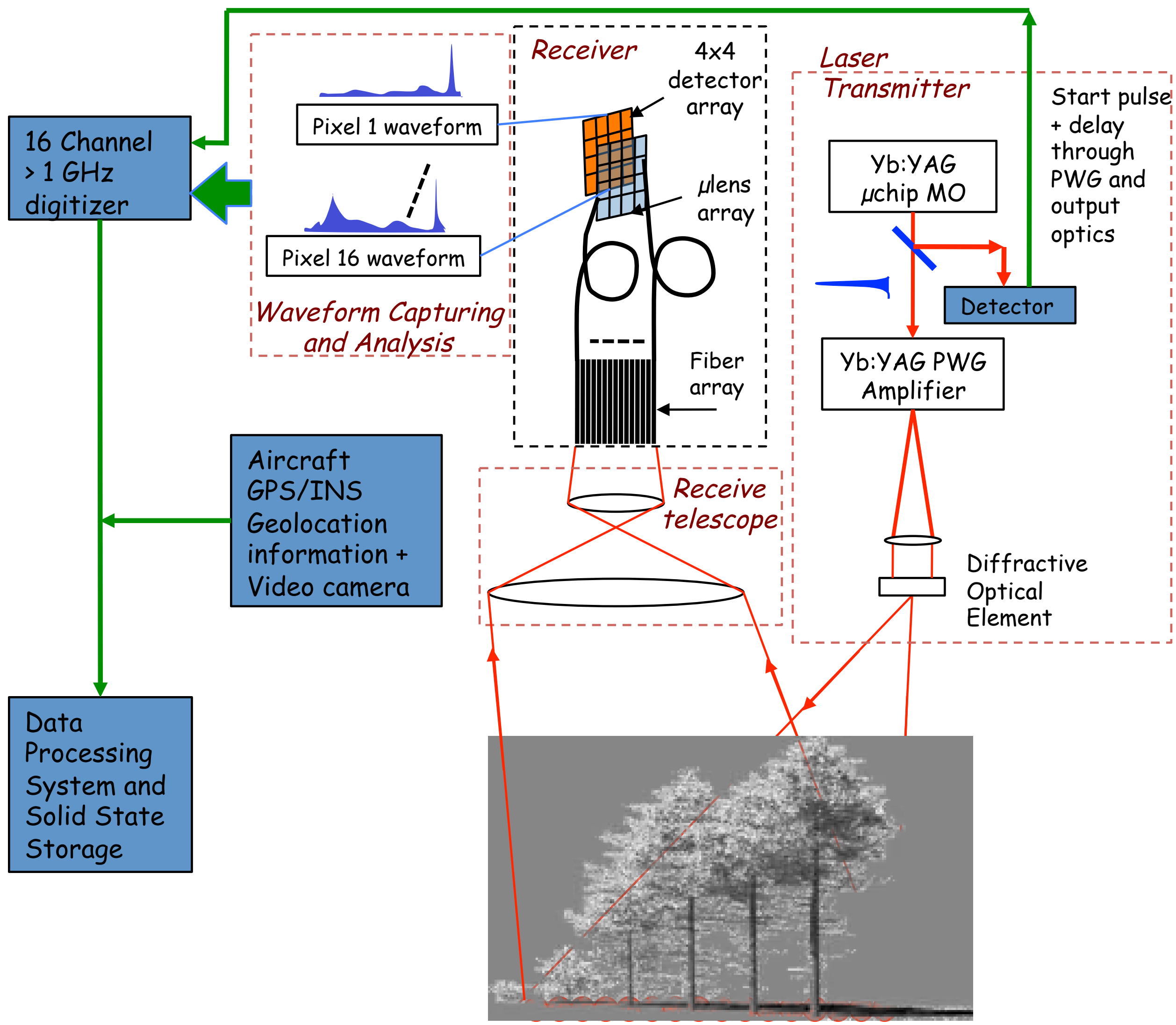
1. Develop and demonstrate scalable laser & detector approaches & technologies to meet the LIST mission requirements.
2. Design and demonstrate an airborne swath mapping altimeter measurements using:
    a. High efficiency, short pulse (< 1 ns) multi-beam laser transmitters;
    b. Higher sensitivity array detectors, waveform capturing;
    c. Similar spatial resolution (spot diameters) as LIST.
3. Characterize performance of key new components/technologies.
4. Demonstrate LIST-type measurements over a variety of surface types, including those of vegetation canopy and substructures.
5. Quantify airborne measurements over a range of signal and optical background conditions and compare/scale to space.
6. Update the LIST mission design and measurement approach based on the technology evaluations and airborne measurement findings.

IIP Airborne Instrument



Laser Transmitter

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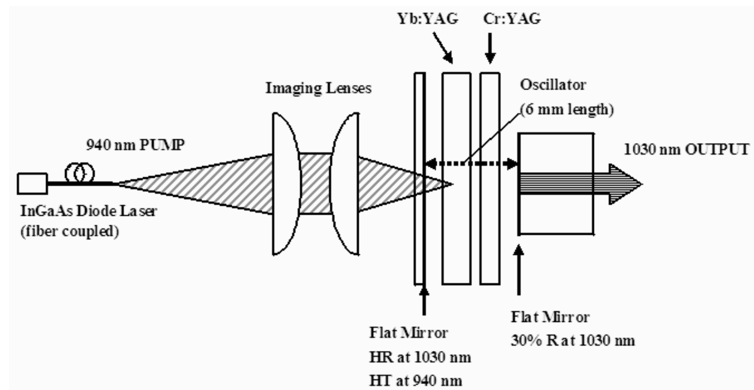
Requirements:

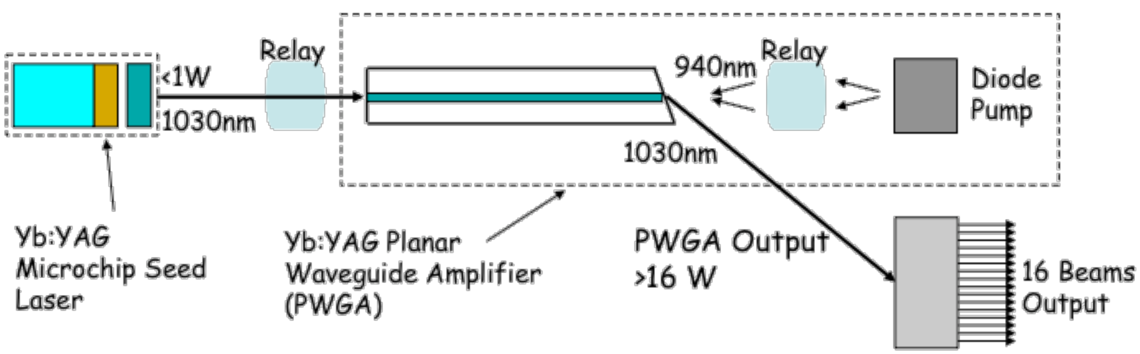
- 10's µJ's and 0.5-2nsec pulses
- High efficiency and small size

Candidate :

- Microchip lasers master oscillator (Raytheon)
  - ~1 ns FWHM, >10 µJ, > 10 kHz
  - 1-2% (Nd:YAG) to ~15% (Yb:YAG) wall-plug efficiency
- Planar waveguide amplifier (Raytheon)
  - Overall MOPA ~15% wall-plug
  - Goal of 1.6 mJ @ 10 kHz, split into 16 beams of 100 µJ each

Master Oscillator - Microchip Laser





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Master Oscillator from Raytheon

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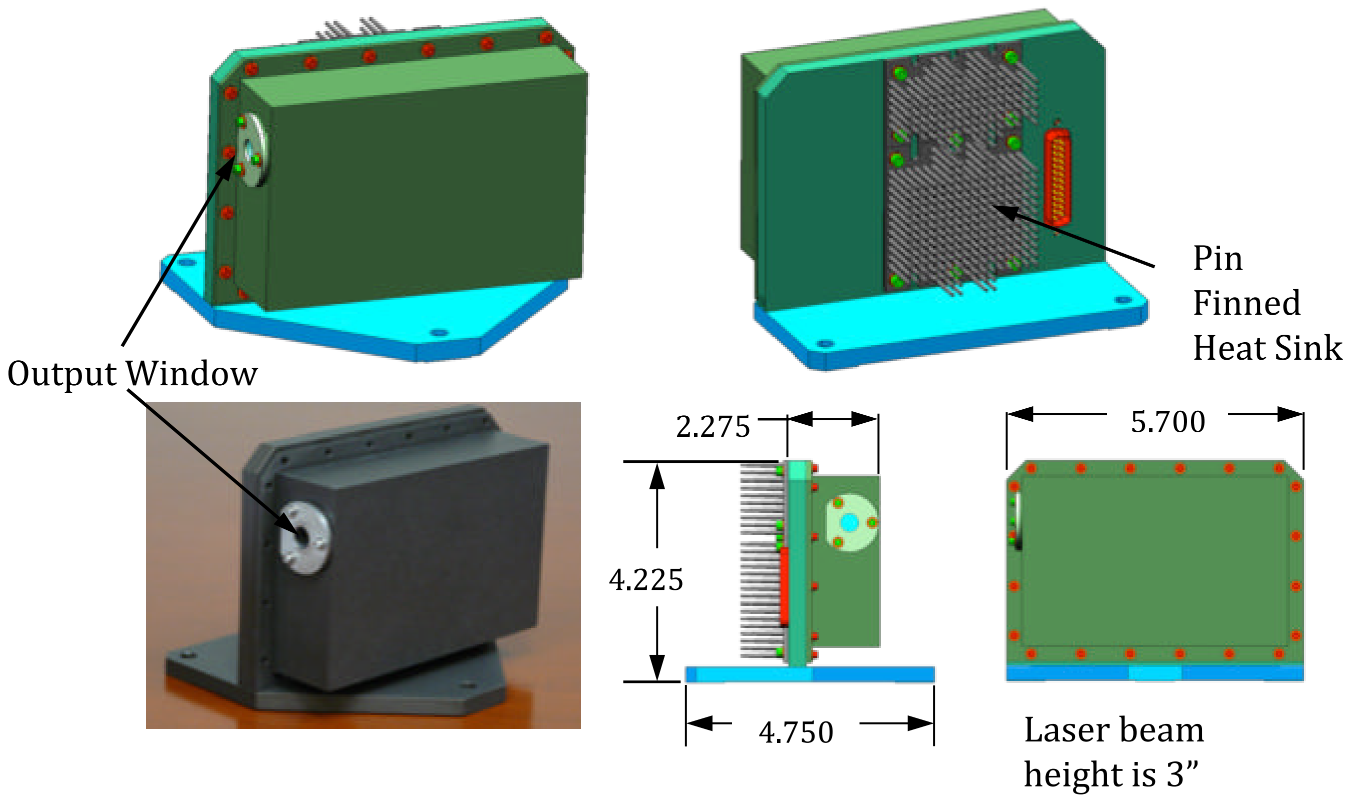

Overall Weight: 2.50 lbs.

100 µJ output with < 1 nS pulse width at 2 kHz

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Intevac Intensified Photodiode (IPD)

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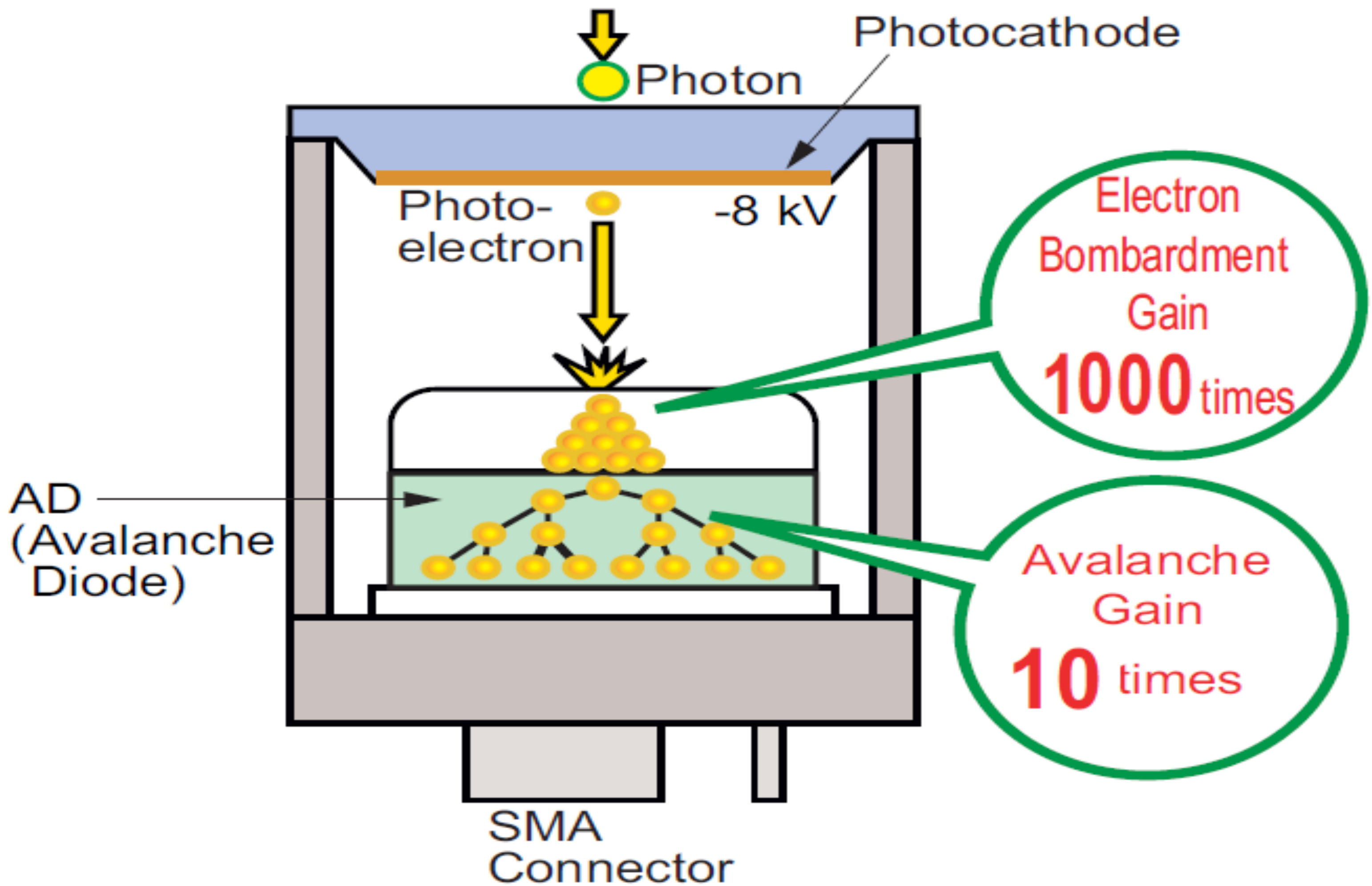
■ Principle



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Multi-element IPD Design from Intevac

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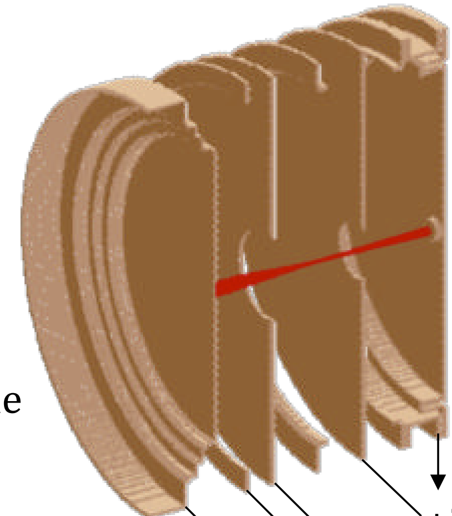
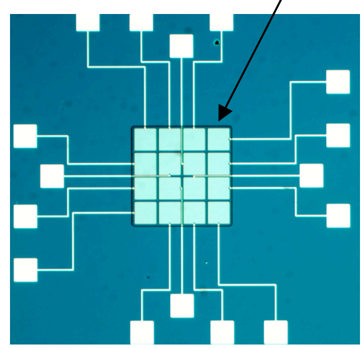
2.1mm diameter TE photocathode



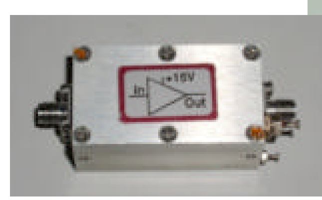
Magnification=0.63

Internal ion trap for cathode protection and large pulse noise reduction

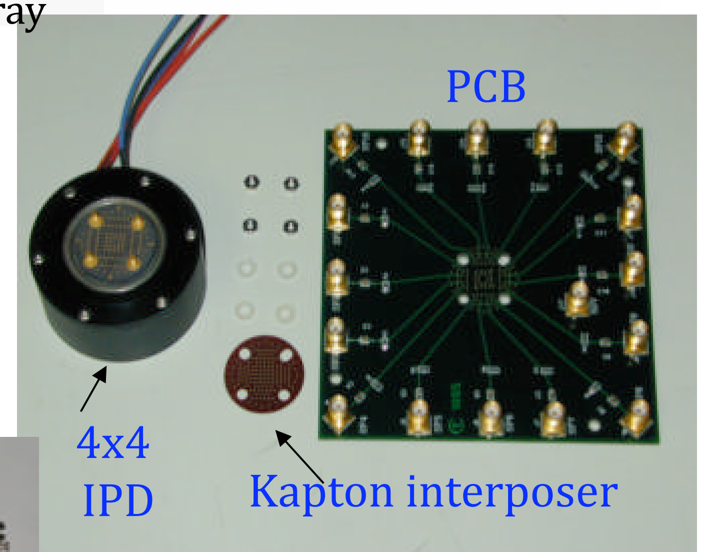
APD anode array



- 100m square
- APD pixels
- 80% fill factor



HV Power Supply



Candidate Airplane for the IIP

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Learjet Model 25

Lear 25 Aircraft Data	
Wingspan	35 ft 8 in (10.84 m)
Length	47 ft 7 in (13.18 m)
Height	12 ft 3 in (3.73 m)
Powerplants	General Electric CJ-610-6, axial-flow turbojet engines

Lear 25 Aircraft Crew / Performance Data	
Pilots	2
Researchers	1-4
Cruise Speed	350 KIAS (.82 MACH)
Range	@ 1,200 Nautical Miles
Ceiling	45,000 ft
Gross Weight	15,000 lb
Useful Load	@ 6,600 lb*

* Fuel/Crew/Research Equipment and other restriction may apply

Instrument Resources

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- Lear 25 Aircraft Resources:
  - Power :
    - 115 VAC 33-40A @ 60 Hz
    - Alternate power available:
      - 115 VAC @400 Hz
      - 28 VDC
  - Volume
    - Installation:
      - The cabin height is 52”. The dimensions of the door are 36” wide by 42” tall.
    - Equipment rack
      - 19” wide X 32” tall
    - Nadir port :
      - 18 ¼” x 21” x 1 ¼” thick quartz window
  - Mass
    - 200 lbs per rack
    - 7500 lbs total payload (including passengers)
  - Ancillary Data
    - Nav data on ARINC

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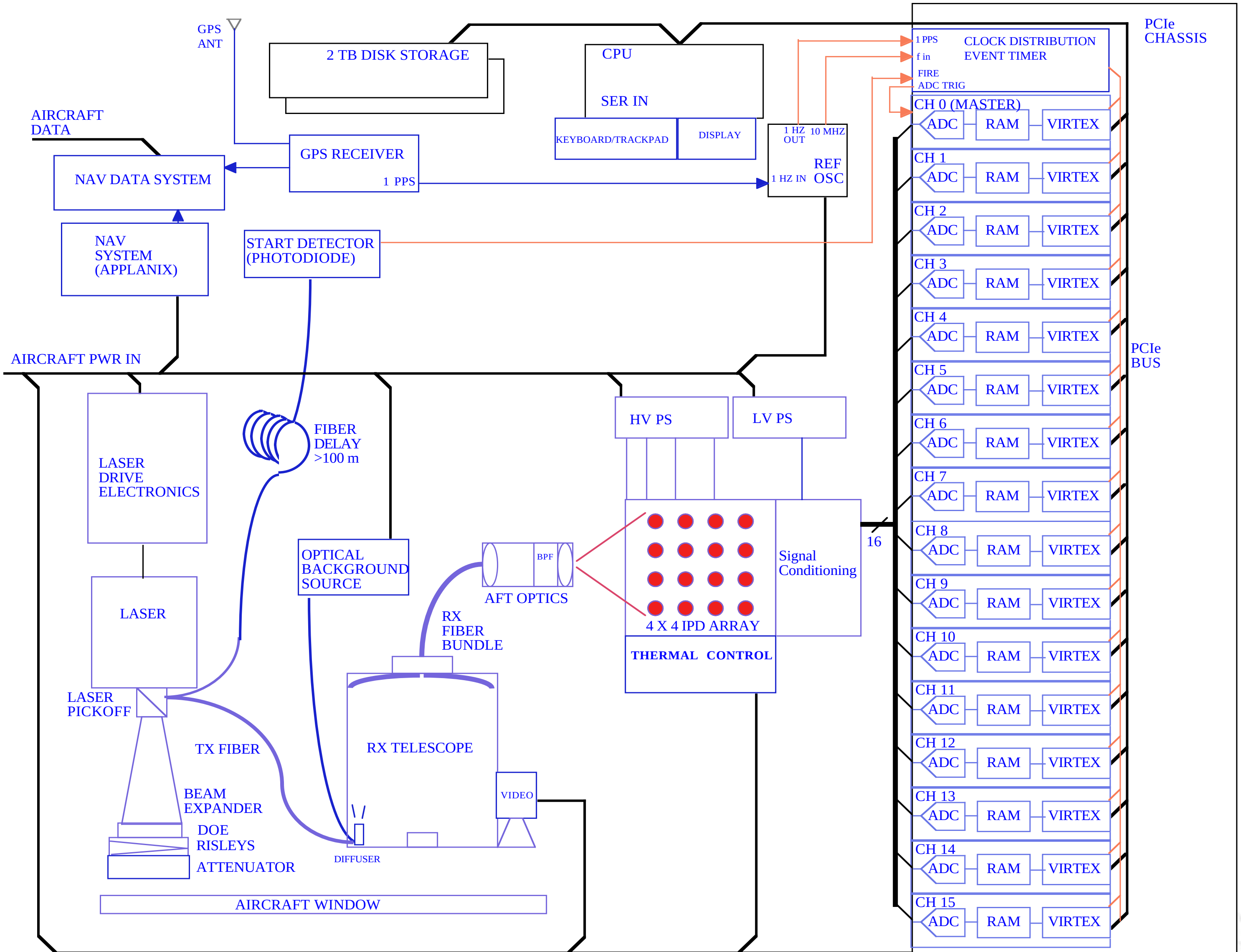
Instrument Block Diagram



Target Sites for Flight Demonstration

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- Closed deciduous canopy, undulating topography
  - Smithsonian Environmental Research Center, Edgewater, MD
    - Very well characterized canopy structure from ground measurements
    - Prior data collections: LVIS, Sigma Micropulse, Commercial Discrete Return
- Closed deciduous canopy, rugged topography
  - Liberty Reservoir, Baltimore County, MD
    - Prior data collections: LVIS, Commercial Discrete Return
- Open coniferous canopy, flat topography
  - Pine Barrens, NJ
    - Prior data collections: Sigma Micropulse, Commercial Discrete Return
- Non-vegetated, rough topography
  - Boulder Field, Hickory Run State Park, MD
    - Prior data collections: SLICER, Commercial Discrete Return
- Bare to sparse vegetation, flat topography
  - Assateague Island National Seashore, MD
    - Prior data collections: ATM
- Urban
  - Ocean City, MD
    - Prior data collections: ATM

Summary

- LIST requires 1000 profiling lines => Measurement efficiency is critical !
- Most demanding measurement: detecting ground through tree canopies
- Data system – will require multi-channel, high sampling rate and bandwidth digitizers with minimum of 8-bit resolution and high data transfer rate.
- Leverage industries and other agencies funded programs on components and systems development.
- Airborne system will demonstrate sixteen profiling lines for a swath of 80 m.
- Engineering flights – April, 2011
- Science flights – September 2011

Acknowledgement

The authors would like to thank NASA ESTO for supporting the Swath Mapper IIP and the detector development effort from the Advanced Component Technology (ACT) program.